Primordial Deuterium Abundance and Cosmic Baryon Density

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ABSTRACT

The comparison of cosmic abundances of the light elements with the density of baryonic stars and gas in the universe today provides a critical test of big bang theory and a powerful probe of the nature of dark matter. A new technique allows determination of cosmic deuterium abundances in quasar absorption clouds at large redshift, allowing a new test of big bang homogeneity in diverse, very distant systems. The first results of these studies are summarized, along with their implications. The quasar data are confronted with the apparently contradictory story from the helium-3 abundances measured in our Galaxy. The density of baryonic stars and gas in the universe today is reviewed and compared with the big bang prediction.

1. Primordial Deuterium and Galactic ^{3}He

People never seem to tire of telling or hearing the triumphant story of the cosmic light element abundances— for example, about how the observed predominance of hydrogen, and the helium mass fraction of roughly 25%, confirm the basic tenets of the big bang theory back to a time of one second, or about how the precisely determined ^4He mass fraction in low-metal galaxies, 0.228±0.005, constrains the cosmic baryon density to be less than $\Omega_b = 0.015h^{-2}$. Here however I will disappoint the avid listeners by focussing attention on the more ambiguous story of the primordial deuterium abundance.

The cosmic baryon-to-photon ratio η is the one astrophysical parameter of big bang nucleosynthesis theory. Everything else follows from pure physics, including predictions for the abundances of light elements. Since we know the photon density today, and since the entropy has changed rather little since nucleosynthesis (as indicated by the perfect Planck spectrum of the background radiation), η determines the physical density of baryons today. In units of the cosmic critical density, the density of baryons is

$$\Omega_b = 3.73 \times 10^{-3} h^{-2} \eta_{10}$$

where $\eta_{10} = 10^{10}\eta$. The theory predicts[1,2] a mass fraction of ^4He

$$Y_p = 0.228 + 0.01\eta_{10}$$

and a primordial number ratio of deuterium to hydrogen

$$(D/H)_p = 4.6 \times 10^{-4} \eta_{10}^{-5/3} = 2.5 \times 10^{-4} \left(\frac{\Omega_b h^2}{0.005}\right)^{-5/3} = 4.5 \times 10^{-5} \left(\frac{\Omega_b h^2}{0.015}\right)^{-5/3},$$

where the last two "high" and "low" values are chosen to illuminate the arguments below. The helium is the best verification of the big bang theory, but the deuterium is the best measure of baryon density, since it is fairly sensitive to η.

The trick is to measure the primordial abundance of this fragile element. Since deuterium is almost impossible to make outside of the big bang, almost all cosmic deuterium is a relic of primordial nucleosynthesis, so it is easy to get a lower limit on $(D/H)_p$. But since the big bang, successive generations of stars have destroyed most of it by burning to heavier elements, which makes any upper limit less straightforward. Indirect constraints on $(D/H)_p$ have been deduced from D abundances in the reprocessed material in the Galactic interstellar medium and from the local abundances of the principal immediate product of D burning, ^3He. Using models of galactic chemical evolution (a weak spot in the argument), the solar abundance of ^3He is used to give an upper limit on the primordial $(D/H)_p$, and thereby a lower limit on the η from standard big bang nucleosynthesis theory[1,2]. This lower limit is higher than observed density of baryons, and therefore provides an argument for abundant baryonic dark matter. If this lower limit is relaxed, the range of allowed η includes lower values where the predicted ^4He abundance lies more comfortably close to observations, where the bound on the number of particle species is relaxed, and where there is almost no baryonic dark matter.

Advances in instrumentation and telescope aperture, especially the Keck telescope and the HIRES spectrograph, have recently enabled observations of high-redshift quasars at high spectral resolution, of the order of 10km sec^{-1}. This has enabled detailed study of the Lyman series absorption lines of hydrogen and its deuterium counterpart (shifted by one part in 3700 to the blue) in high-column-density foreground absorbers[3,4]. The first such observations revealed absorption consistent with a high abundance of deuterium in one very metal-poor absorbing cloud in one quasar (Q0014+813), around $D/H \approx 2 \times 10^{-4}$ by number, which is about a factor of five higher than previous guesses for the primordial D/H based on observations of local ^3He abundances, and an order of magnitude greater than the interstellar value[5]. As of this writing, the abundance in one other, slightly more enriched cloud has been measured[6] closer to the ISM value. One Ly series absorption line system can always be dismissed as a chance hydrogen interloper masquerading as deuterium[7], while a low D/H can be attributed to destruction, so we require more systems for a clearer picture to emerge of the true primordial value. The technique will in time be applied to many other quasars and absorbers, establishing critical tests we have never had before of big bang theory: abundances at cosmological distances, in different environments and at different cosmic epochs, and in pristine material which has undergone relatively little chemical evolution (see figure 2). If more than one high D/H value is found, it will lead to a major revision of thinking about this isotope. While not conclusive, the first data have raised at least the possibility that the primordial D/H might be rather high, and the global baryon density rather low, motivating a reexamination of the interpretation of cosmic abundances and the data on the density of baryons.

The measure of $^3He/H$ most widely used for estimating $(D/H)_p$ comes from measurements of the solar wind, both from direct exposure experiments and from meteorites, of $^3He/^4He$[8], which are used to infer that the abundances of the presolar nebula by number were $D/H = 2.6 \pm 1.0 \times 10^{-5}$, $^3He/H = 1.5 \pm 0.3 \times 10^{-5}$, $(D + {}^3He)/H = 4.1 \pm 1.0 \times 10^{-5}$. These are taken as Galactic or solar-circle averages for the purpose of defining constraints on primordial abundances. A skein of theory then connects the presolar abundance with the primordial one. The main reason why the new Keck D/H observations come as a surprise was that they give a D/H a factor of five larger than ^3He abundances in the solar system.

Figure 1– Comoving lightcone in an Einstein-deSitter model, showing space-time location of Q0014+83 and the "Chaffee cloud" where Songaila et al. estimated D/H from Lyman series absorption. Vertical position corresponds to cosmic scale factor; the bottom of the cone is $t = 0$, the top is the present epoch. Horizontal position is the present-day proper distance; the apex is our position, and the classical particle horizon is the bottom of the cone. The great distance of the cloud tests the cosmological principle applied to primordial abundances, the first measurement probing the early past world lines of distant points— the distant interior of our past light cone. The high redshift of the absorber provides a direct probe of pristine material from the big bang; this cloud has metal abundances estimated at less than 10^{-3} of the solar value.

In the standard picture the bulk of primordial D in the Galaxy is burned to ^3He in protostellar collapse. Galactic chemical evolution models[9,10,11] show that D/H can be reduced in this way to its present interstellar value ($\approx 1.5 \times 10^{-5}$, ref. 5) from any plausible initial value. However, in the low mass stars which now dominate the chemical recycling of the interstellar medium (ISM), the bulk of the material is assumed to be never heated to the higher temperature required to burn the ^3He, so the bulk of the primordial D reappears in the ISM as ^3He when the envelopes are ejected. For the galaxy as a whole, the sum $(D+^3He)/H$ therefore only increases with time, so that even the solar ^3He abundance can be used to set constraints on $(D/H)_p$. This is why the evolution of ^3He is critical.[12]

The only other useful measure of cosmic $^3He/H$ comes from radio emission maps of highly ionized HII regions in the Galaxy[13,14]. The column density of $^3He^+$ is estimated from the brightness in the 8.665 GHz hyperfine transition line, and the column (squared) density of H^+ or $^4He^+$ is estimated from radio recombination lines. Balser et al. use this data and a simple model of the gas distribution to obtain reliable estimates of $^3He/H$ in 7 Galactic HII regions, and "preliminary" abundances and limits in 7 more. Two of the most reliable ones are W43 and W49, with low values $^3He/H = 1.13 \pm 0.1 \times 10^{-5}$ and $^3He/H = 0.68 \pm 0.15 \times 10^{-5}$ respectively. There appears to be a real range of values, with W3 for example measured at $^3He/H = 4.22 \pm 0.08 \times 10^{-5}$, and some are consistent with still higher values. There may be a trend with galactocentric radius in the sense that lower values tend to lie within the solar orbit and higher values outside it.

Note that these results do not mesh with the standard interpretation of the solar ^3He; quite aside from the Keck D/H observations, empirical evidence in the Galaxy suggest that stellar populations on average actually get rid of ^3He.

- The Solar System value $(D+\ ^3He)/H$ is greater than the interstellar one; if $(D+\ ^3He)/H$ were steadily increasing, it ought to be less, because of the elapsed time since the formation of the solar system.
- The ISM shows large variations in $^3He/H$, which argues that one ought not take any one point, such as the solar system, as an average of the Galactic abundance, and that simple uniform-mixing models are unlikely to accurately model the abundances at any given point, such as the solar system.
- The gradient with Galactic radius goes the wrong way; if stars are creating ^3He on average, it ought to be highly enriched towards the Galactic center, like other heavier elements are.
- If we adopt instead the lowest $^3He/H$ value in ISM (W49) as the primordial one, to be consistent with the idea that $^3He/H$ cannot decrease, thereby assuming that the additional ^3He found at other sites is Galactic in origin as required in the standard picture, *then* SSBN requires a large $\Omega_b h^2 = 0.075$, in which case it also predicts an excessive ^4He abundance $Y_p \approx 0.26$. The observed value is $Y_p = 0.228 \pm 0.005$ [15,16], which is marginally inconsistent even with the SBBN prediction for solar $^3He/H$, $Y_p = 0.242$.

A destruction mechanism is therefore desirable both for improving the consistency of big bang theory and for interpreting the Galactic $^3He/H$ data. It is not clear whether such a mechanism operates in the Galaxy. One recently proposed mechanism[12] is based on mixing envelope material in low mass stars down to high temperature after they reach the giant branch, so that the ^3He is destroyed before the material is ejected. This process, originally postulated to explain the observed change in C and N isotope abundances[17,18] as low mass stars ascend the giant branch, would also destroy ^3He. It remains to be seen how important it is for the population as a whole, but the possibility of such effects motivates caution in using highly processed material for estimating $(D/H)_p$.

2. Cosmic Baryon Bookkeeping

It is interesting to compare the density of baryons inferred from either SBBN argument with the density of baryons and dark matter found in the universe.

Let us review a number of different measures of global densities, summarized in figure 2. Each column shows both estimated statistical errors in the method and the variation with the (still uncertain) Hubble constant h, where $h = H_0/100\mathrm{km\ sec}^{-1}\ \mathrm{Mpc}^{-1}$.

The first column shows the contribution of baryons to the mean density, estimated from standard Big Bang nucleosynthesis (SBBN). The current canonical range[1,2, 9] is shown, $\Omega_b h^2 = 0.010 - 0.015$, which leads to the best concordance with a low value of $(D/H)_p$. Most reliable is the upper limit of this range, which appears firmly fixed by a variety of abundances. Indeed, it represents a 3σ departure from the best value[15] for the primordial ^4He abundance, $Y_P = 0.228 \pm 0.005$. Some have argued[19] that one should instead fit the best value of Y_P, requiring $\Omega_b h^2 \approx 0.005$, the lower indicated range. This estimate of $\Omega_b h^2$ agrees with the recent possible detection[3] of high deuterium.

A direct lower limit on gas density is imposed by quasar absorption line statistics, shown in the second column. A large sample of quasars provides an accurate census of all neutral hydrogen in the universe at $z < 4$ through Lyα absorption along their sightlines. At high redshift, the bulk of the HI is in high column density damped Lyman α (DLyα) absorbers, with column density in the range $N(HI) \approx 10^{20-22}\mathrm{cm}^{-2}$. These contribute[20] an integrated density $\Omega_{\mathrm{DLy}\alpha} h = 2.9 \pm 0.6 \times 10^{-3}$, which should be taken as a lower limit on the total density of such absorbers[21].

The third column shows an example of traditional baryonic bookkeeping[22]: estimate the mass-to-light ratio of a population, then use the mean cosmic luminosity density (here, in V band and solar units) to find a contribution to the mean mass density. We use spiral galaxies, as they dominate the luminosity density. Our Galactic disk out to 700pc height has $(M/L)_V = 5\,\mathrm{M}_\odot/\,\mathrm{L}_\odot$, with most of the mass contained in stars. If all spiral disks have the same mass-to-light ratio, we can use an estimate[22] of the luminosity density ($j_0 = 1.7 \pm 0.6 \times 10^8\,\mathrm{L}_\odot/Mpc^3$ in V) to get the integrated density of all the material in spiral galaxy disks. (Note that the errors shown are just those from the estimate of j_0). Similarly there are several mass measurements of the Galaxy halo mass from local group satellite galaxy orbits[23] and from local group timing, which yield masses of at least $1 \times 10^{12}\,\mathrm{M}_\odot$. With a Galactic luminosity[22] of $1.4 \times 10^{10}\,\mathrm{L}_\odot$ this corresponds to an overall lower limit of $(M/L)_V = 71\,\mathrm{M}_\odot/\,\mathrm{L}_\odot$ for the Galaxy. If we assume that all spirals have a similar amount of halo material per disk light, we obtain the estimate shown for spiral halos, $\Omega_{\mathrm{halos}} h > 4.4 \pm 1.5 \times 10^{-2}$.

A variant of this argument is shown in column four. Persic and Salucci[24] have integrated the luminosity functions of spiral and elliptical galaxies separately, with their M/L estimated directly from dynamics, allowing h to be eliminated. They estimate $\Omega_b = 1.5 \times 10^{-3}$ from ellipticals and $\Omega_b = 0.7 \times 10^{-3}$ from spirals, which is systematically lower, and probably more accurate, than the previous argument. I have estimated errors to again be at the 30% level. It is interesting that the total contribution from gas in groups and clusters is comparable to these, $\Omega_b = 1.5 \times 10^{-3} h_{50}^{-1.3}$, in spite of the fact that rich clusters contain only about 1% of galaxies, and that the clusters out to the Abell radius were assembled from about 1% of the total comoving volume, but there ought to be large errors attached to this estimate.

Figure 2– Estimated contributions of various components to the global density, in units of the cosmic critical density. Each column shows a vertical range from estimated internal errors, as well as a variation across each column due to the range of possible values of the Hubble constant, $0.5 < h < 1$. Column 1 shows the range for Ω_b allowed by SBBN, both for the canonical limits derived from solar system ^3He abundance, and for the lower value estimated from the recent possible detection of high primordial D/H in a single QSO absorber and the best measured value of primordial ^4He abundance Y_p. Column 2 shows the contribution of neutral hydrogen in quasar DLyα absorbers at $z \approx 3.5$; although Wolfe's errors are shown, this should be taken as a lower limit for the HI density. Column 3 shows estimates of the global density of spiral galaxy disk stars and halos, obtained from local (Galactic) M/L estimates combined with the mean cosmic luminosity density. The lower band represents $M/L = 5\,\mathrm{M}_\odot/\,\mathrm{L}_\odot$, representative of the local disk material out to about 700 pc, and the upper band ($\Omega_{\rm halos}$) represents $M/L = 71\,\mathrm{M}_\odot/\,\mathrm{L}_\odot$, corresponding to a Galaxy halo mass of 1×10^{12} solar masses. Column 4 shows a similar estimate but based on integration of luminosity functions and dynamically estimated M/L; the band represents Persic and Salucci's estimate for spiral and elliptical galaxies, with errors added by me, and the upper line represents their estimate including cluster gas. Columns 5 and 6 show global densities estimated from the ratio of components in the Coma cluster. Column 5 shows the dark matter, gas and star components where the sum is assumed to have $\Omega = 1$; Column 6 shows the same ratios, but where the total density is fixed to be 0.1.

Column five is based on just the Coma cluster, where we have the most uniformly reliable data[25]: it shows cosmic densities based on the estimated mass for Coma ($M = 1.1 \pm 0.18 \times 10^{15} h^{-1}\,\mathrm{M}_\odot$, $M_{gas} = 5.45 \pm 0.98 \times 10^{13} h^{-5/2}\,\mathrm{M}_\odot$, $M_{stars} = 1.0 \pm 0.2 \times 10^{13} h^{-1}\,\mathrm{M}_\odot$), assuming that Coma is representative of their cosmic ratios and that $\Omega_{PDM} = 1$. The high baryon density is in apparent conflict with SBBN. Ironically, the high M/L of galaxy clusters, regarded since Zwicky as the strongest evidence for plentiful cosmic dark matter, is now apparently due to low L (i.e., the bulk of the baryons being in gas rather than stars), and not to high M (i.e., having a more representative sample of the high cosmic dark matter density.) The well-studied central region of Coma has about the same mix of visible baryons and dynamical dark matter as the Milky Way. This is shown in column five, which again shows the empirical ratios of mass to gas and stars in the Coma cluster, only now assuming instead that $\Omega = 0.1$ for the dark matter.

Where then are the baryons? Common thinking is that most of the baryons reside in a photoionized IGM— everywhere outside of clusters, there is the same large amount of gas per galaxy as there is inside, but it is not seen because it is not hot and dense enough to emit X-rays. But it remains difficult to reconcile the large number of cluster baryons with the small Ω_b required by even the highest SBBN limits. Galaxy halos contain about the same amount of material as the total baryonic density for canonical (low D/H) SBBN; a popular option is to make the halos out of compact objects (MACHOs; see Carr's contribution in this volume). But making halos out of MACHOs prevents us from using these baryons in the IGM; baryons would have to be converted into MACHOs in galaxies, and gas in clusters, so the formation of the MACHOs would need to be at a low redshift, accessible to observation. The lower value of $\Omega_b h^2 = 0.005$ does not provide even enough baryons to make galaxy halos. There is no easy way to reconcile the large baryon abundance of clusters with this very low baryon density; a cluster like Coma would need to gather baryons from a volume twenty times bigger than the volume from which it gets galaxies.

One route to reconciliation is the introduction of inhomogeneities in the baryon distribution within the early big bang, on either small or large scales. Small scale inhomogeneities, which can arise naturally from QCD or electroweak phase transitions, create zones of neutron-rich nucleosynthesis[26, 27, 28, 29], which naturally creates extra deuterium[26] compared to a homogeneous model; these models however do not appear capable of exceeding the usual SBBN upper limit[29]. There could also be more baryons if some of them gravitationally collapse into a compact form at or before recombination, due to large-scale inhomogeneities [30,31]. Some noise distributions naturally produce approximately correct abundance distributions in the diffuse baryons that do not collapse, so in principle the total density of baryonic matter could be greater than classical nucleosynthesis bounds, although they cannot easily solve the Coma cluster problem, which necessarily involves diffuse gas. Such ideas can be constrained or eliminated by a variety of gravitational microlens probes of the nature of dark matter[32,33,34,35, 36], and can also be tested directly, by measuring abundances in different locations (eg, different quasar absorbers.) It is important to emphasize that the overall concordance between the different light element abundances remains good, which indicates that the basic SBBN picture is a good approximation— and that there is no reason to think that this situation will change.

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5. References

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